

Control/Structure Interaction

Design Methodology

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By

Dr. Hugh C. Briggs, Deputy Manager

William E. Layman, Technical Manager

JPL CSI Program

Jet Propulsion Laboratory

California Institute of Technology

Pasadena, CA

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Hugh C. Briggs, Deputy Technical Manager
William E. Layman, Technical Manager

Jet Propulsion Laboratory
4800 Oak Grove Drive
Pasadena, CA 91109

Abstract

The Control/Structure Interaction Program is a technology development program for spacecraft that exhibit interactions between the control system and structural dynamics. The program objectives include development and verification of new design concepts - such as active structure - and new tools - such as a combined structure and control optimization algorithm - and their verification in ground and possibly flight test. The new CSI design methodology is centered around interdisciplinary engineers using new tools that closely integrate structures and controls. Verification is an important CSI theme and analysts will be closely integrated to the CSI Test Bed laboratory. Components, concepts, tools and algorithms will be developed and tested in the lab and in future Shuttle-based flight experiments.

The design methodology is summarized in block diagrams depicting the evolution of a spacecraft design and descriptions of analytical capabilities used in the process. The multiyear JPL CSI implementation plan is described along with the essentials of several new tools. A distributed network of computation servers and workstations has been designed that will provide a state-of-the-art development base for the CSI technologies.

The NASA Control/Structure Interaction Program

The NASA CSI Program is an element of the Control of Flexible Structures Task in the NASA Civilian Space Technology Initiative. Three NASA Centers participate in the CSI Program: Langley Research Center, Marshall Space Flight Center and the Jet Propulsion Laboratory. This multiyear program to develop and validate new design technologies is organized around five elements: Systems and Concepts, Analysis and Design, Ground Test Methods, Flight Experiments and Guest Investigation Program. The CSI program goal is to develop validated technology that will be needed to design, verify and operate interactive control/structure systems to meet the ultraquiet structure requirements of 21st century NASA missions.

The CSI Program will integrate the advances made in other discipline technology programs to make the new spacecraft design methodology (see Figure 1). Controls programs such as Computational Control will develop a new generation of tools for multibody simulation, multibody component representation, and control analysis and synthesis. Structures technology programs such as Computational Mechanics will develop advanced finite element analysis codes. CSI will integrate these tools into a multidisciplinary environment and develop additional tools such as simultaneous structure and control optimization methods, and conceptual design tools for flexible spacecraft structure/control architectures. New CSI systems

and concepts, such as active structure, will be developed and integrated into focus mission design examples.

Other developments that will enable high performance, flexible spacecraft design include an investigation of microdynamics and development of ground test methods for controlled flexible spacecraft structures. Microdynamic characterizations of spacecraft components such as joints and struts will identify the linearity of typical elements when dynamic motions are restricted to the submicron regimes required for future spacecraft. In addition, disturbance sources will be characterized at the microdynamic level to support analysis of ultraquiet spacecraft systems.

CSI Philosophy

A new philosophy is behind the CSI Design Methodology that supports improved integration of the traditional engineering disciplines utilized by the design team. These concepts emphasize integration, information sharing, and an environment that facilitates the development of new ideas and analytical capabilities. Flexible spacecraft design is a multidisciplinary process that involves several traditional engineering disciplines. For example, most organizations are structured to provide the design team with engineers from configuration design, controls, structures, mechanical design and electronics design. A major CSI objective is to demonstrate better integration of these disciplines in a working environment.

Optimal spacecraft design requires engineers who are interdisciplinary, who understand the operation and analysis of various spacecraft subsystems and who can capitalize on that understanding. The benefit of developing and utilizing the new CSI engineer is the extra margin of performance that can be gained by simultaneous optimization and the increased effectiveness of the design team that results. Beyond this, systems are sufficiently complex and must meet such intricate constraints that an interdisciplinary approach is required to generate feasible designs. Fortunately, in most cases spacecraft system design does not require great, in-depth knowledge in any one engineering discipline. CSI system engineering, if supported by a good analytical environment, needs only a working-level understanding of the central disciplines.

Spacecraft design is typically executed in a team environment because of the complexity, size and engineering breadth required. The design team is staffed with several engineers, each contributing one or more of the traditional engineering capabilities, but all working the systems issues on multiple fronts. The team is led by a system engineer who coordinates the team efforts, maintains the team focus and the uniformity of analysis. The team reports to one or more decision makers when analyses alone cannot form a basis for a choice and judgements are required. Organizations differ in their approach to decision making, in some instances giving a single manager sweeping decision-making authority, and in other situations constructing a tiered or layered decision-making system. In all cases, the design team and decision makers are acting on behalf of one or more groups of stakeholders and/or sponsors. The design methodology must be compatible with such organizational environments and surroundings, providing support and drawing resources as necessary.

To foster the development of interdisciplinary engineers and to facilitate the execution of the design process, the team members need to be collocated. Information exchange is critical to the design process and, although electronic media can help, geographical dispersion is a

significant impediment. Synergy occurs quite readily when structures engineers and controls engineers work side by side with the opportunity to share techniques, brainstorm ideas and teach each other tricks of the trade. Collocation is essential to building and maintaining an atmosphere of enthusiasm and excitement.

The design team must be supported by a modern computer environment to realize the potential of the new methodology. State-of-the-art tools are required and the boundaries of practical computation are always being stretched by new mission requirements. The computer system must provide rapid iteration and convergence of the spacecraft design if insight and ingenuity are to provide further system performance gains. Support for traceability, documentation, and reporting must be inherent in the computer environment and not simply a task that is levied after the completion of the design process. It is the computer system underlying the CSI methodology that will enable the verification of the spacecraft design in ground and flight test, and verification is an essential step in the methodology.

CSI Methodology

Systems built by humans have a readily observed life cycle that consists of progressive stages of activity from design to production to retirement (see Table 1). Various systems progress through the life cycle at different rates and organizations provide different tools for segments of the cycle. The CSI technology development activities primarily support the early system design activities. Certain analysis tools such as simulations can also be used to support mission operations. Other developments in computer aided engineering could provide access mechanisms to fabrication steps through design transfers. The design process is conveniently partitioned into three segments, conceptual design, preliminary design and detail design, although the boundary between the last two is expected to soften as computer-based analytical capabilities improve. This partitioning allows exploitation of the best features of existing, large-scale modeling and analysis tools, as well as the smaller model optimization abilities of the new tools. See Figure 2.

Conceptual Design

Experience indicates that most of the really significant trades and design decisions are made by the system design team in arriving at a system concept that, based upon simple analysis, should meet most objectives and constraints. This was borne out during the early design steps of a Focus Mission Interferometer. The system conceptual design is typically depicted in a mechanical layout incorporating all major subsystems.

Several significant choices may be imbedded in the conceptual design that may be difficult to change or revisit. For example, the location, arrangement and connectivity of essential mission critical elements is defined and used as the basis for subsequent analysis. Without efficient design tools, most certainly computer-based, this step can not be repeated without significant elapsed time and labor. Aspects of the statement of the design problem might include maneuver sequence and operational scenarios. Since these form the initial conditions for the design team, any significant change would certainly invalidate the conceptual design.

Conceptual design trades are typically based upon engineering judgement and backed by simple analyses. Little documentation is usually prepared to send forward with the completed

design. The design team at this stage is quite small, perhaps consisting of the systems engineer and one or two discipline engineers. The justification, assumptions and trades are carried mentally and the design is advanced until too many ideas get lost in the process. Often, the end user is consulted frequently as the design progresses and this raises questions about the users' true intentions. The design progresses until a meaningful problem can be stated and answered with minimal number of uncertain aspects.

When the design process is viewed as the ultimate selection of a single point design from a large, multidimensional design parameter space, it can be seen that the decisions leading to the conceptual design substantially constrict the spaces to be considered in the following design steps. Indeed, the fundamental operating characteristics of the system are set by the end of the conceptual design phase.

The CSI methodology emphasizes the early application of analytical methods to the conceptual design phase. To demonstrate this, a conceptual design tool will be developed which will (1) support definition and tracing of requirements, (2) provide 3-dimensional modeling for concept depiction, and (3) provide integrated analytical methods to facilitate system trades.

Preliminary Design

With one or two system concepts in hand as a result of the conceptual design phase, the space of design parameters can be explored with new numerical optimization and performance analysis tools. The design variables might include structural parameters such as truss element areas and control parameters such as feedback gains. This simultaneous optimization of structure and control parameters will lead to a better system optimum than sequential optimization of the individual subspaces. Multiple objective optimization techniques, better known as vector optimization, allow the performance functions to include system mass, system power, closed loop performance, robustness and system cost. Notice that these are competing and incommensurate objectives and that application of vector optimization will lead to a family of (Pareto-optimal) solutions.

In general, the design variables fall into the two categories of either continuous or discrete variables. Member cross-sectional area is an example of a continuous design variable and actuator locations are examples of discrete variables. The optimization with respect to the continuous variable can be based upon homotopy or multiple objective techniques while model changes or dynamic programming is required for the discrete variables. Furthermore, certain performance functions, for example those that are not expressible as analytic functions of the design variables, might be utilized in a final manual analysis step using traditional analysis tools. System settling time and certain frequency domain transfer function properties are typical examples of such performance measures. For these metrics, numerical gradients might be computed a priori for representative locations in the design space and utilized with interpolation in subsequent optimizations.

The limitations of current hardware and optimization algorithms will place restrictions on the size of the design problem at this stage. Models with less than a few hundred degrees of freedom will be required initially to keep the design session interactive. This is sufficient to allow the designer to explore the intricacies of the system design space and perform design trades with analytical support. The results of these analyses and optimizations are presented to the

project decision maker to select from the design space one or two concepts with tightly bounded decision parameter ranges, to take forward into detailed design.

Detailed Design

Within certain restrictions, a detailed evaluation and tuning of the surviving candidate design(s) can be adequately executed based upon current state-of-the-art tools. The traditional large model analysis faithfully represents the physical behavior of the system and can be validated with component, subsystem and system level testing of most constituent technologies. However, if significant non-linear behavior is present in the problem or system models must be developed from many large component models, significant limitations remain.

In this phase, the system design parameters must be tuned to meet detailed performance specifications and all phases of the mission must be analyzed. Realistic operating scenarios must be developed to provide maneuver profiles, environmental effects and disturbance characterizations. The modest optimization models must be expanded or extrapolated into detailed models and analyzed in the realistic mission contexts.

Several analysis systems currently exist that support this analysis phase. Representative systems include Boeing's IAC/ISM, SDRC's I-DEAS and NASA's IMAT. Further development in this technology will be to improve data manipulation and retrieval mechanisms, to improve the human-machine interface and presentation manager, and to include new analytical methods, for example, optics and thermal analysis.

Implementation of the CSI Methodology - The Design Environment

The design environment represents the instantiation of the methodology and consists of several elements. The following section will address the computer systems and the laboratory testing facilities. The software and analytical tools were described in the preceding methodology overview section.

The CSI computer system is a distributed network-based system consisting of workstations and servers (Figure 3). Laboratory testing computers are attached to the network to support the close integration of verification in test to the development of systems concepts and tools. Sufficient commercial technology exists to support a heterogeneous equipment set based upon standard network interfaces. For example, systems from Apple, DEC, Sun, Apollo, HP, Silicon Graphics and others can all participate in an Ethernet network using TCP/IP. This capability supports various user preferences and capabilities as well as providing the mechanism to protect existing corporate investments in computer systems.

The distributed system utilizes servers for those functions not allocated to the per-engineer workstations. Large computers, such as a CRAY or departmental VAX, function as compute servers to provide an execution site for large, compute intensive jobs. Other servers might provide specialized capabilities for animation, data base management or communications. Most workstation companies make it financially attractive to collect most of the system disk resources in one or more file servers that support some form of a network disk system (e.g. Sun's NFS). These file servers are repositories for large data sets, system executables and application libraries.

The workstations must support the interactive design environment with excellent speed and graphics. The CSI methodology requires computation of intermediate sized (ie. 100+ states) problems and presentation of solid models on the workstations. Representative derived requirements for workstations are: 3-10 MIP 32 bit CPU, 12-16 Mb memory, Unix operating system, 200 Mb disk, Ethernet interface, 3-D vector graphic accelerator and windowed presentation manager with a mouse.

The network environment also extends into the laboratory where verification and validation experiments are executed on the CSI Test Bed. The computing environment internal to the lab is shown in Figure 4. The four functions are: real-time control, experiment supervision, modal analysis and software development. Individual systems can be readily purchased to perform each function although it is possible to configure certain commercial systems to perform multiple duties. In any case, the software development system will most probably not be instantiated in the laboratory, using individual analyst workstations and the experiment supervisory computer instead.

The real-time control computer system will be a distributed, multiprocessor computer based upon commercial VMEbus products. The operating system supports remote consoles, software loading and unloading, a prioritized scheduler and shared memory message passing. An excellent example is VxWorks from Wind Rivers although the underlying kernel requires additional multiprocessor extensions. Analysts will prepare simple control subroutines on their workstation and produce a load module just as they would any program for execution. Remote login facilities are provided for access to any real-time CPU and a C-like shell provides the operator interface. Products such as Dbx-Works provide source level symbolic debugging.

The experiment supervisory computer provides the laboratory operator console and overall control of the Test Bed. This system monitors and logs environmental variables such as temperature and air velocity, monitors a panic button during experiment execution and collects measurements from the external truth sensor. Remote access from any network workstation allows remote execution of experiments.

The modal analysis and data acquisition system is a standard commercial product and supplies a necessary function found in all dynamics laboratories. To characterize the structural dynamics of the test article, a modal survey can be performed utilizing a large number of accelerometers distributed over the structure. This is typically done to verify open loop system models but should also be an integral part of closed loop system performance measurement. Results are available to any analyst via the network.

For precision controlled structures, the laboratory environmental requirements are quite severe. Noise and seismic disturbance constraints will require all personnel and actively cooled electronics to be sequestered in an adjacent control room. During tests, the test chamber must be unoccupied, closed, and carefully maintained at constant temperature. This will require development of control procedures for remote experiments and forms the basis for emulation of on-orbit flight experiments. Shuttle command, communication and control features can be readily emulated with the network-based computer system and the computational capabilities of space-qualified computers can be replicated in the ground test hardware. Figure 5 illustrates scale and complexity of a test bed that models a space-based interferometer.

The CSI Design Handbook

To provide the essential technology transfer mechanism, a CSI Design Handbook will be developed over the life of the CSI program. This Handbook will contain verified design standard practices, definitions, examples and an implementation guide. It will be published by NASA with contributions from all participating centers in intermediate and final forms. Table 2 shows the Table of Contents of the Handbook.

CSI Testing Requirements

CSI will validate the system concepts, components and tools in realistic ground tests. Where the ground environment precludes acceptable verification due to such effects as the gravity field, seismic, acoustic disturbances and size limitations, flight tests will be proposed to complete the development and validation of the technology.

Testing is recognized as an essential component of the design process. The design methodology will include close coupling of the analysis with the testing and evaluation of results. This will foster verification of new system concepts and designs as well as provide analytical support for new ground test techniques. In addition, the CSI flight experiments will be designed to develop techniques for extending ground testing methods to on-orbit flight tests.

As a result of integrating testing into the design process, several capabilities must be built into the ground test facility. Interactive evaluation of control system performance must be provided to explore system phenomena and to enable reconciliation of measured behavior with predicted behavior. To validate the new optimization methods and to evaluate system robustness properties, substitution of any structural element will be provided without dismantling large subsections of the test article. Support for remote investigation of system performance via the electronic network, already mentioned as a requirement for CSI analysts, will also include support for off-site Guest Investigators. This access includes all test measurement data as well as the control programs of the real-time control computer. Finally, emulation of all essential Shuttle command, communications and control features that impact proposed flight experiments will be provided.

Summary

Control/Structure Interactions is a NASA technology development program to develop new methods for designing integrated control/structure systems and to develop new methods to test control of large flexible CSI systems. Missions of the near future such as advanced Earth observation platforms and large, flexible antennas will be significantly enhanced, and new classes of missions such as large optical interferometers and large optical telescopes will be enabled.

Acknowledgement

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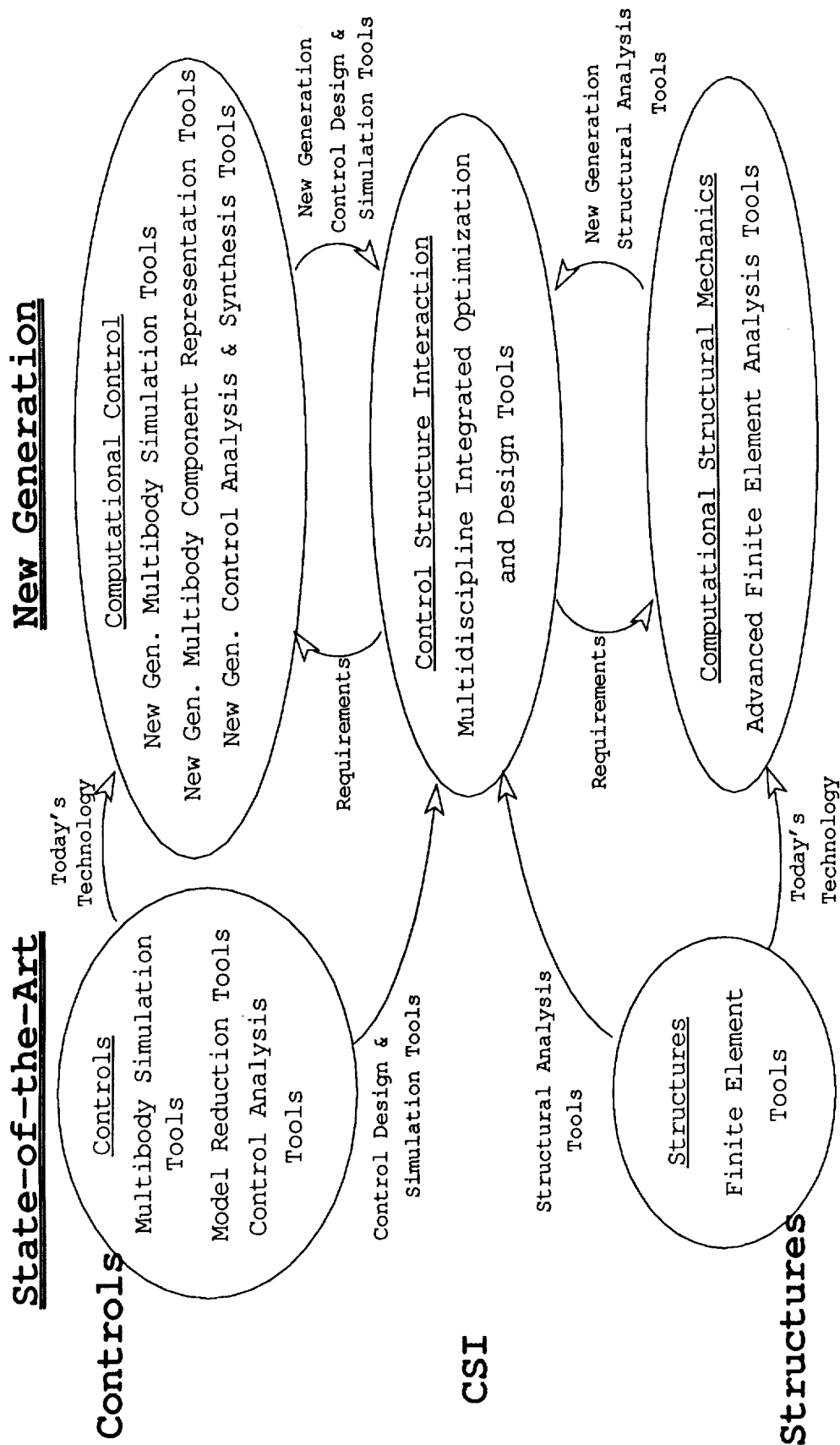
Table 1. System Life Cycle

- Pre-Project Planning
- Conceptual Design
- Detail Design
- Fabrication and Production
- Functional and Environmental Testing
- Mission Operations
- Retirement

Table 2. CSI Design Handbook Table of Contents

Philosophy
Procedure
Worked Examples
Lessons Learned
Appendices
 Tool Descriptions
 Implementation Guides

Figure 1. Relationship Between Controls, Structures, and CSI Tools



Preliminary Design:



Figure 3. CSI Computing Network

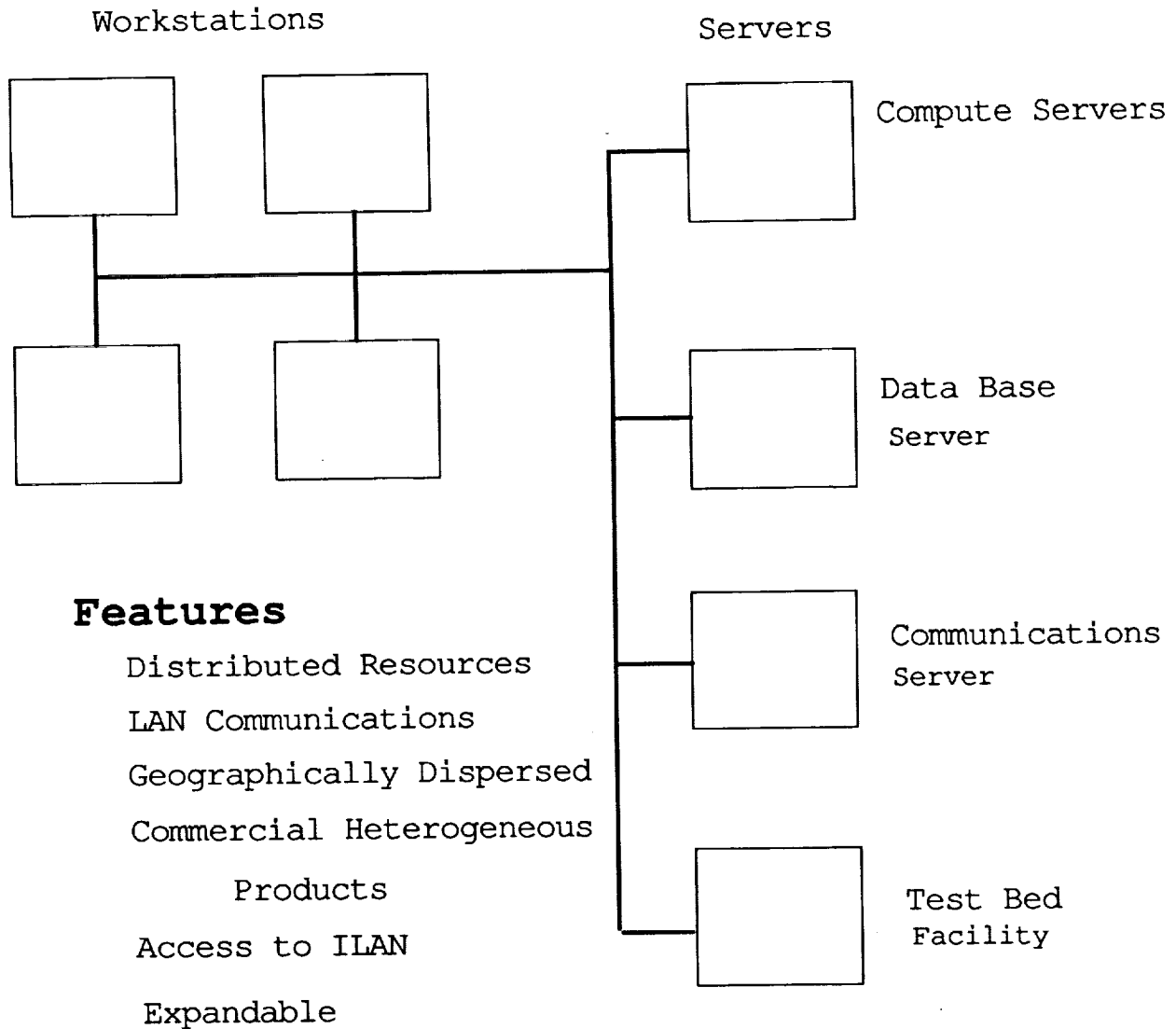


Figure 4. Test Bed Computing Environment

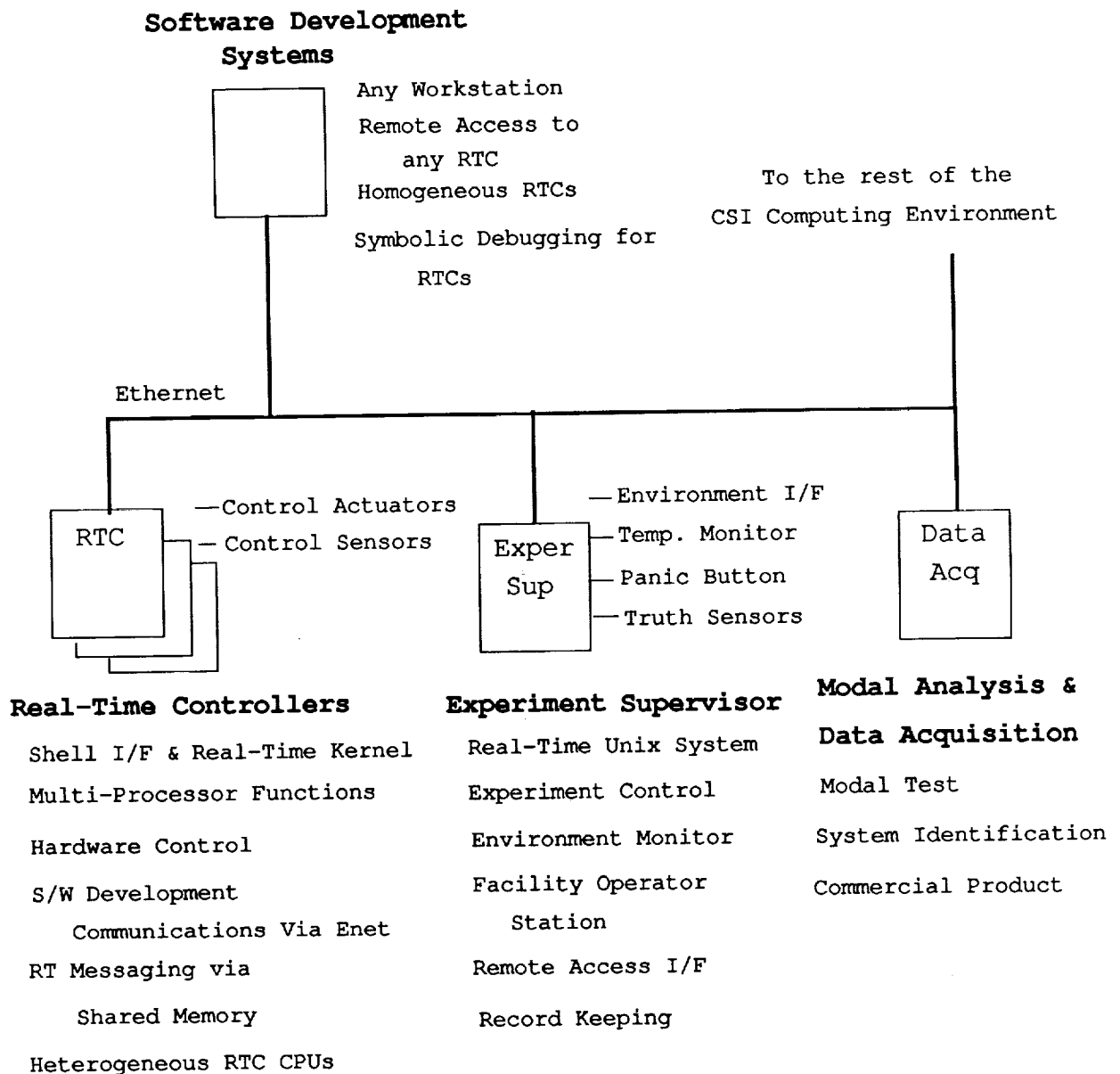


Figure 5. Integrated Controls and Structures Laboratory

